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SMOKE EVALUATION OF A MODIFIED J-57 COMBUSTOR

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16. Abstract

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SUMMARY

An experimental investigation was conducted to reduce smoke emission from a J-57 turbojet engine burning ASTM A-1 fuel by making modifications to the primary zone of the combustor. Tests were performed with a single J-57 combustor liner that was installed in a 12-inch- (30.5-cm-) diameter pipe. Mixing and percentage airflow in the primary zone of the combustor were increased by varying the geometry of combustor dome and liner air-entry openings. Smoke was evaluated at simulated sea-level takeoff conditions with a combustor inlet total pressure of 181 psia (12.3 atm), inlet total temperature of 600° F (589 K), combustor reference velocity of 54 feet per second (16.5 m/sec), and a fuel-air ratio of 0.013. At this operating condition, the final configuration had a measured smoke number of about 24 compared to a smoke number of 64 for the unmodified J-57 combustor. The effects of combustor inlet total pressure, inlet total temperature, and fuel-air ratio on smoke number for the final configuration and the unmodified J-57 combustor are presented. Smoke number was calculated from the measured reflectivity of combustor exhaust smoke samples collected on filter paper. The altitude relight capability of the final configuration is shown to be significantly poorer than that of the unmodified J-57 combustor; however, the intended ground application for this engine did not warrant further development of ignition capability. The final configuration had the same total pressure loss as the unmodified J-57 combustor but a slightly poorer combustion efficiency and exit temperature profile.

INTRODUCTION

Reference 1 describes a gas turbine combustor test facility that was designed and built at the NASA Lewis Research Center and is capable of operating at combustor inlet total temperatures as high as 1200° F (922 K) without vitiating the airstream. The inlet air is preheated in a shell and tube heat exchanger that is fed with hot gases from J-57 engines. These turbojet engines have been modified to use natural gas fuel in order to minimize atmospheric pollution. An additional facility is being designed and built at the NASA Lewis Research Center that will use a similar preheat system; however, A-1 jet fuel will be burned in the J-57 engines.

The purpose of the program described in this report was to develop a means for reducing smoke emission from the J-57 combustor burning A-1 jet fuel. Methods for reducing smoke emission by combustor redesign are discussed in references 2 to 6. The general approach followed in this investigation was to reduce smoke emission by both lowering the primary zone fuel-air ratio and increasing the primary zone mixing intensity.

Tests were conducted with a single J-57 combustor liner installed in a 12-inch- (30.5-cm-) diameter pipe at simulated engine operating conditions. Smoke measurements were made by passing exhaust gas samples through a continuously moving filter tape. The quantity of smoke is expressed by a smoke number which is related to the reflectivity of the smoke trace on the filter paper. The smoking characteristics of the final combustor configuration are compared to the standard J-57 combustor. The combustion efficiency, total pressure loss, exit temperature profile, and relight capability of these two combustors are also compared. In addition, the smoke performance of other modifications that were investigated during the course of the program are summarized. The effects of these design changes on the emission levels of gaseous pollutants including unburned hydrocarbons, carbon monoxide, and nitric oxide were not investigated.

TEST INSTALLATION

A single J-57 combustor liner installed in a 12-inch- (30.5-cm-) diameter pipe was connected to an inlet source of compressed air and an exit exhaust system as shown in figure 1. The inlet air was heated by a counterflow tube heat exchanger as described in reference 7. Airflow rates and combustor pressures were regulated by remotely controlled valves upstream and downstream of the test section.

A schematic drawing of the combustor test ducting is shown in figure 2. The combustor reference area was defined as the cross-sectional area inside the 12-inch- (30.5-cm-) pipe test section which is 0.775 square foot (7.2×10^{-2} sq m) or approximately one-eighth of the annular cross-sectional area of the combustor housing in the J-57 engine which contains eight combustor liners. The combustor inlet diffuser ducting was made as a constant area circular pipe having a 12-inch (30.5-cm) diameter in order to simplify fabrication. Also, to simplify fabrication, the combustor exit transition was made as a constant circular duct of 9.74-inch (0.247-m) diameter. The combustor length measured from the fuel nozzles to the exit temperature measurement plane was 27.3 inches (0.694 m).

Unless noted otherwise in the text, tests were performed with the standard fuel nozzle manifold from the J-57 engine which consists of six duplex nozzles as shown in figure 3. Tests were performed with either the standard nozzle shroud or the modified nozzle shroud shown in figure 3. The fuel flows to the primary and secondary chambers of the duplex nozzles were controlled by separate throttle valves. A typical flow calibration using water for a set of six duplex nozzles is shown in figure 4. All tests were performed with ASTM A-1 fuel except for a single reference test in which natural gas was used. A low pressure drop gas nozzle was used for the natural gas tests.

INSTRUMENTATION

Airflow rates were measured by square-edged orifices, located upstream of the air preheater, that were installed according to ASME specifications. Fuel flows were measured by turbine-type flowmeters. Pressures were measured by strain gage transducers.

The axial locations of the test instrumentation planes are shown in figure 2(a). The cross-sectional positions of the smoke sampling probe, thermocouples, and combustor static pressure taps are shown in figure 2(b). Exit temperatures were measured by 40 bare junction Chromel-Alumel thermocouples positioned at the centers of equal areas as shown in figure 2(b).

Smoke Sampling System

The smoke sampling probe which is shown in figure 5 was designed to sample the exhaust stream at five positions on the centers of equal areas. The inner diameter of the probe inlets was sized for near-isokinetic sampling at the sea-level takeoff (SLTO) condition and the throat immediately downstream of each inlet was sized to choke at a total sample flow rate of about 15 cubic feet per minute (7.1×10^3 cc/sec) at the SLTO condition.

A schematic drawing of the smoke sampling system is shown in figure 6. The sampling line length was about 30 feet (9.2 m) long. The pressure and temperature upstream of the measuring filter were maintained at about 2.5 psig (1.7×10^4 N/sq m gage) and 400° F (478 K), respectively. Pressure was regulated by a valve in the vent line. Only about 4 percent of the total sample line flow rate passed through the measuring filter; the remainder was passed through the vent to the atmosphere. The smoke sample passed into the filter tape through a 1/2 inch (1.27 cm) wide by 1/4 inch (0.64 cm) long slot in the filter head, giving a 1/2 inch (1.27 cm) wide smoke trace on the filter tape which traveled at a speed of 4 inches per minute (10.2 cm/min). Whatman No. 4 filter paper was used.

The sampling system used had several shortcomings. There was an indeterminate amount of leakage at the filter head. The leakage could not be eliminated without either slowing or stopping the movement of the filter tape. The desired sampling rate through the filter tape was 0.6 cubic foot per minute (280 cc/sec); however, probably due to the leakage, there was an overall variation in sample flow rate from sample to sample of about ±10 percent.

As a result of the aforementioned problems, the absolute accuracy of the acquired smoke data may be questionable. However, since the same procedures were repeated for each combustor test and the readings obtained from different tests were found to be repeatable, the readings were considered a significant measure of the relative smoke emission obtained from each combustor configuration that was tested. Furthermore, the simplicity of the sampling system that was used enabled a rapid screening of each combustor being tested. A comparison of smoke measurements obtained from the standard J-57 combustor with unpublished J-57 engine smoke measurements acquired from a test program described in reference 8 indicated that agreement was quite good.

SMOKE DATA REDUCTION

The absolute reflectivity of the smoke traces was read with a Welch Densichron. The instrument was calibrated using gray scale tiles supplied by the manufacturer. All sample traces were read over a gray background with an absolute reflectivity of 31.5 percent. The absolute reflectivity of the clean Whatman No. 4 filter paper read over the gray background was 77.5 percent.

The density of the smoke sample was expressed as a smoke number which is defined by the following equation:

$$\text{Smoke number} = 100\left(1 - \frac{R_S}{R_W}\right)$$

where R_S is percent absolute reflectivity of sample and R_W is percent absolute reflectivity of clean filter paper (77.5 percent).

All smoke traces were obtained at a nominal filtration rate of 0.3 cubic foot of sample gas (standard conditions) per square inch of paper (1320 cc/sq cm).

COMBUSTOR MODIFICATIONS

A sketch of the production combustor liner is shown in figure 7. Table I summarizes the modifications made to the production combustor during the course of the development program. The locations of these modifications are shown in figure 7. Table II lists the open hole area for each air-entry station for all combustor models tested. A summary of the overall performance and the primary zone airflow distribution of each combustor is presented in table III.

The geometry of the final configuration, model 5-G will be described in this section and compared to the design of the production combustor, model 1-A. The design and performance of all intermediate models will be described in more detail in the appendix. Photographs of the production combustor, model 1-A and model 5-G are shown in figures 8 and 9, respectively. A comparison of the airflow distribution curves for these two combustors is shown in figure 10. The airflow distribution was calculated from combustor air-entry hole geometry using the computer program of reference 9. The calculated airflow entering the primary zone of model 5-G is 34.6 percent compared to a value of 24.7 percent for model 1-A. The primary zone was arbitrarily defined to include the liner volume upstream of the trailing edge of hole row 1 on the outer diameter of the liner.

The following modifications to the production combustor, model 1-A, were incorporated into model 5-G:

(1) Six slots were cut out of the dome (fig. 9(a)). Each slot had an open area of 1.01 square inches (6.53 sq cm). Six 1/2-inch (1.27-cm) wide V-gutters (baffles) were installed forward of each slot (fig. 9(a)).

(2) Five 3/4-inch- (1.9-cm-) diameter short tubes were installed at station 13 in-line with each swirler except the swirler in-line with the spark plug. A 1/2-inch- (1.27-cm) diameter hole was located at station 1 in-line with spark plug.

(3) All holes at stations 2, 3, and 4 were blocked.

(4) A modified nozzle shroud was substituted for the standard nozzle shroud (fig. 3). There are twelve-0.0785-inch- (0.199-cm-) diameter air-entry holes in each standard nozzle shroud. The hole diameter was increased to 0.093 inch (0.236 cm) for the modified nozzle shroud thus increasing the flow area by 41 percent.

RESULTS AND DISCUSSION

The smoke emission characteristics of model 5-G and model 1-A will be compared for a range of operating conditions. In addition, the combustor performance including combustion efficiency, total pressure loss, exit temperature profile, and ignition will be compared for these two combustor configurations. Detailed smoke emission and combustor performance results at the takeoff condition for all combustor configurations that were tested are discussed in the appendix.

Smoke Number

Effect of combustor inlet total pressure. - The variation of smoke number with combustor inlet total pressure is shown in figure 11. These data were obtained at a combustor inlet total temperature of 600° F (589 K), a combustor reference velocity of 54 feet per second (16.5 m/sec) and a fuel air ratio of 0.013. The data shown at 181 psia (12.3 atm) corresponds to a simulated takeoff condition. The smoke measured at the combustor exhaust is considered to be visible for values of smoke number greater than 25. The choice of this value of smoke number for the threshold of smoke visibility is quite arbitrary since other variables including exhaust nozzle diameter, engine type, and atmospheric background affect smoke visibility for a given smoke number.

As expected, the smoke number for both model 5-G and 1-A increased with pressure; however, at the simulated takeoff condition the smoke number has been reduced from a value of about 64 for model 1-A to a value of about 24 (below the visibility threshold) for the model 5-G. The reduction in smoke emission is attributed to increased airflow entering the upstream portion of the primary zone, increased airflow at the immediate vicinity of the fuel nozzles, and increased mixing intensity.

Effect of combustor inlet total temperature. - The variation of smoke number with combustor inlet total temperature is shown in figure 12. These data were obtained at a combustor inlet total pressure of 181 psia (12.3 atm), a combustor reference velocity of 54 feet per second (16.5 m/sec), and a fuel-air ratio of 0.013. The trend of increasing smoke number with decreasing inlet temperature is similar to previous results presented in reference 10. The slope of the data for model 5-A is similar to that for model 1-A. The data shown at a temperature of about 600° F (589 K) are for the simulated takeoff condition.

Effect of fuel-air ratio. - The variation of smoke number with fuel-air ratios is shown in figure 13. These data were obtained at a combustor inlet total pressure of 181 psia (12.3 atm), an inlet total temperature of 600° F (589 K), and a combustor reference velocity of 54 feet per second (16.5 m/sec). The smoke number at these conditions is shown to be rather insensitive to fuel-air ratio for the range considered. The very slight increase in smoke number at lower fuel-air ratios may be due to poorer fuel atomization at lower values of fuel nozzle pressure drop.

Combustor Performance

The presence of smoke in the combustor exhaust stream is usually not detrimental to combustor performance; however, the design changes required to eliminate smoke may seriously penalize combustor performance. Furthermore, combustor modifications made to eliminate smoke may increase the amount of unburned hydrocarbons, carbon monoxide, and nitric oxide in the exhaust. The concentrations of these gaseous pollutants were not investigated in this program.

Combustion efficiency. - The combustion efficiency is defined as the ratio of the actual enthalpy rise to the theoretical enthalpy rise as calculated by the method of reference 11. The variation of combustion efficiency with fuel-air ratio is shown in figure 14. These data were obtained at a combustor inlet total pressure of 181 psia (12.3 atm), an inlet total temperature of 600° F (589 K) and a reference velocity of 54 feet per second (16.5 m/sec). Both models exhibit a nearly constant value of combustion efficiency over the range of fuel-air ratio investigated; however, the combustion efficiency is shown to drop from about 99.5 percent for model 1-A to about 95.5 percent for model 5-G. No effort was devoted to the improvement of the model 5-G combustion efficiency.

Combustor total pressure loss. - The isothermal total pressure loss (percentage of inlet total pressure) is plotted against combustor reference Mach number in figure 15. The pressure loss is shown to be identical for models 1-A and 5-G. The total pressure loss at simulated takeoff conditions is about 1.5 percent corresponding to a reference Mach number of 0.035.

Combustor exit temperature contours. - The exit temperature contours for models 1-A and 5-G are shown in figure 16 for the simulated takeoff condition. The model 5-G is shown to have a hotter core and a larger temperature gradient that the model 1-A. The exit temperature pattern factor increased from a value of 0.15 for model 1-A to a value of 0.30 for model 5-G. The pattern factor is defined as the ratio of the difference between the maximum and average exit temperature to the average temperature rise.

Ignition and blowout. - The ignition and blowout limits for models 1-A and 5-G are compared in figure 17 for a reference Mach number of 0.05 and a fuel-air ratio of 0.02. Both ignition and blowout characteristics deteriorated significantly due to the primary zone changes made in the model 5-G. In addition the ignition point shown for the model 5-G at 15 psia (1 atm) and 100° F (311 K) was not repeatable and could only be reproduced by dropping the reference Mach number to a value of about 0.025. The model 5-G could be ignited at simulated engine starting conditions corresponding to an inlet total pressure of 15 psia (1 atm), inlet total temperature of 85° F (303 K), reference Mach number of 0.02, and a fuel-air ratio of 0.026. No attempt was made to improve the altitude relight characteristics of the model 5-G.

Combustor durability. - Several tests were performed at simulated takeoff conditions in which the model 5-G combustor was coated with temperature sensitive paint. No unusual hot spots were noted on the combustor after the completion of these tests. A 15-hour endurance test was performed on the model 5-G combustor at the completion of the test program. The test was performed with cylic 1-hour runs at the simulated takeoff condition with 5-minute periods between the shutdown of each test run and the reignition for the next test run. No deterioration in durability, performance, or smoke number was observed during these tests.

SUMMARY OF RESULTS

A production combustor was modified to reduce smoke emission. The following results were obtained for the best configuration designated as model 5-G operating at the simulated takeoff condition:

1. The smoke number was reduced from about 64 to 24.
2. Combustion efficiency was reduced from about 99.5 to 95.5 percent.
3. Combustor total pressure loss was unchanged.
4. The exit temperature pattern factor increased from 0.15 to 0.30.
5. The minimum ignition limit for a fuel-air ratio of 0.02, a reference Mach number of 0.05, and an inlet temperature of about 90° F (305 K) was raised from 6 psia (0.4 atm) to above 15 psia (1 atm).

CONCLUDING REMARKS

The smoke emission level of a production combustor was reduced to below the visible thershold. This was not accomplished without suffering some deterioration in combustion efficiency and exit temperature profile and a significant reduction in altitude relight capability. No effort was devoted to the improvement of combustor performance because the resulting level of performance was considered satisfactory for the required slave engine application. In addition, no consideration was given to the gaseous exhaust emission level. Considerably more effort would have been required to reduce the smoke emission level below the visible threshold without sacrificing combustor performance, especially altitude relight.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, November 24, 1970,
720-03.

APPENDIX - DESCRIPTION OF DESIGN MODIFICATIONS

AND SUMMARY OF OVERALL PERFORMANCE

The essential features of each model tested will be described in this section. Each configuration has been assigned a model number consisting of a number which designates a particular production liner and a letter which designates a sequential modification to that particular liner. Each model was screened at the following simulated takeoff conditions:

(1) Combustor inlet total pressure: 181 psia (12.3 atm)

(2) Combustor inlet total temperature: 600° F (589 K)

(3) Combustor reference velocity: 54 feet per second (16.5 m/sec)

(4) Fuel-air ratio: 0.013

The smoke number, combustion efficiency, total pressure loss, and exit temperature pattern factor were determined for each model at simulated takeoff and are listed in table III.

Also listed in table III are values for the ratio of primary zone to total air-entry area and for the ratio of mixing zone to total air-entry area. The total air-entry area is defined to include the swirler open area, holes in the dome, liner dilution holes, and liner film cooling openings. The primary zone air-entry area is arbitrarily defined to include all air entry ports forward of and including station 1 (fig. 7) but excluding liner film cooling openings. The mixing zone air-entry area is arbitrarily defined to include all air-entry ports foward of and including station 13 (fig. 7) but excluding liner film cooling openings. In general, increasing the mixing zone air-entry area appeared to have a more significant effect on reducing smoke emission than increases within the primary zone.

The major criterion used to judge the performance of each model was the smoke number determined at the simulated takeoff condition. Liner durability and exit temperature pattern factor were also important considerations used to evaluate performance. In general, the combustion efficiency measured at the simulated takeoff condition did not fall below about 95 percent for any model that was tested; and therefore did not have any particular influence on the thought that went into the design of these configurations. An effort was made to maintain a value of total pressure loss close to that of the production combustor. The model 5-G described previously in the sections COMBUSTOR MODIFICATIONS and RESULTS AND DISCUSSION was selected as the best configuration on the basis of satisfactory smoke number, acceptable combustor efficiency, exit temperature profile, and durability.

Model 1

Model 1-A, the production combustor liner is described in the text in the sections COMBUSTOR MODIFICATIONS and RESULTS AND DISCUSSION. Model 1-B was identical to model 1-A except for the incorporation of the six injectors shown in figure 18 in place of the production duplex nozzles. Each injector, which was designed for low pressure drop injection of natural gas, had six 0.140-inch (0.356-cm) orifices. The model 1-B was tested with natural gas as a means of (1) checking out reliability of smoke sampling system and (2) establishing lowest possible smoke reading with a "clean" fuel. A smoke number of zero was obtained at the simulated takeoff condition.

Model 2

Model 2-A was identical to model 1-A except for the addition of 54 1/4-inch (0.64-cm) holes to the dome as shown in figure 19. As shown in table III, the increase in the ratio of mixing zone to total air-entry area from 19.1 to 24.7 percent resulted in an increase in smoke number from 64 to 70. No particular significance can be attributed to the observed increase in smoke number because the reading error becomes quite large for samples with smoke numbers greater than about 60.

Model 2-B which was identical to model 2-A, except that 41 percent of the air-entry holes at station 5 were blocked off, did not have a significantly lower value of smoke number. A further increase to the primary zone airflow distribution in model 2-C (fig. 20) resulted in a reduction in smoke number to 49; however, this was not considered to be a significant reduction in smoke. It should be noted that in going from model 2-A to model 2-C that the ratio of primary zone to total air-entry area increased from 29.7 to 40.0 percent while the ratio of mixing zone to total air-entry area only increased from 24.7 to 25.6 percent.

The model 2-D was identical to the model 2-C except for the substitution of a larger swirler and simplex fuel nozzles as shown in figure 21. The larger swirler which contained eight 45° turning vanes increased the swirler open area from 0.046 to 0.069 square foot (4.27×10^{-3} to 6.4×10^{-3} sq m) disregarding the blockage of the turning vanes. Tests were performed with both 12- and 13.5-gallon-per-hour (45×10^{3} - and 51.3×10^{3}-cc/hr) nozzles (flow rate capacity at 100-psi or 68.9×10^{4}-N/sq m differential). The smoke number was reduced to a level ranging from 24 to 32 using the 12-gallon-per-hour (45.6×10^{3}-cc/hr) nozzles; however, the 13.5-gallon-per-hour (51.3×10^{3}-cc/hr) nozzles provided a smoke number of 60. The fuel nozzle pressure drops for the 12- and 13.5-gallon-per-hour (45.6×10^{3}- and 51.3×10^{3}-cc/hr) nozzles were 435 and 320 psi (302 and 222 N/sq cm), respectively. The lower smoke number for the 12-gallon-per-hour

(45.6×10^3-cc/hr) nozzle may be attributed to a deeper fuel penetration for the corresponding higher nozzle pressure drop.

Further modifications to the liner airflow distribution (models 2-E, 2-F, and 2-G) did not result in smoke emission levels below that of the model 2-D with 12-gallon-per-hour (45.6×10^3-cc/hr) nozzles. The model 2-D modification was discarded in favor of the model 5-G to avoid the necessary redesign of the fuel manifold system.

Model 3

The model 3 combustor series consisted mainly of changes to increase the primary zone airflow distribution, but resulted in smoke numbers no better than 38 (model 3-C).

Model 4

The main feature of the model 4-A combustor were the six 1.01-square-inch (6.53-sq cm) slots cut out of the dome as shown in figure 22. The incorporation of deflector plates behind these slots in model 4-B (fig. 23) resulted in a reduction in smoke number to 20 from a value of 38 for model 4-A. This modification thus provided a satisfactory smoke emission level; however, further testing in both the model 4 and model 5 series revealed a burnout problem with the deflector plates. The results obtained from model 4-B, however, did illustrate the necessity for introducing the additional primary zone airflow into the immediate vicinity of the fuel nozzle.

The lowest measured smoke number obtained from any modification was a value of 11.0 obtained with model 4-C, which was a version of model 4-B incorporating a $10\frac{7}{16}$-inch (26.5-cm) shroud around the liner. The improvement is attributed to more intensive mixing due to increased pressure loss; however, this model had a rather poor exit temperature profile.

Model 4-D was similar to model 4-B except for a small increase in primary zone airflow; however, the difference in smoke number between models 4-B and 4-D was not significant.

In models 4-E, 4-F, 4-G, and 4-H, the deflectors behind the slots in the dome were removed in an attempt to eliminate burnout problems, and primary zone airflow was further increased by means such as adding more holes to the dome as in model 4-G (fig. 24); however, rather poor smoke emission levels were experienced in all of these configurations. The poor performance of these configurations is attributed to poor mixing. It should be noted that even the addition of externally supplied high pressure air to model 4-F which passed through the primary fuel nozzle (fuel introduced only through secondary fuel nozzle) failed to lower the smoke emission level.

Model 5

Model 5-A was similar to model 4-B except that a different method was used to mount the deflector plates (as shown in fig. 25) and the liner air-entry geometry was unchanged from model 1-A. A smoke number of 14 was obtained; however, as occurred previously with model 4-B, the deflector plates were badly burned.

In models 5-B, 5-C, and 5-D, the deflector plates were removed and other methods of blocking the dome slots were investigated such as shown for model 5-C in figure 26; however, all of these configurations had unsatisfactory smoke numbers. The installation of six 3/4-inch- (1.9-cm-) diameter short tubes at station 13 (fig. 17) in model 5-E resulted in a reduction in smoke number to a value of 27. Similar modifications were reported as being effective in reducing smoke emission in reference 2. The ratio of mixing zone to total air-entry air was reduced from 33.9 to 25.9 in going from model 5-E to model 5-F resulting in an increase in smoke number from 27 to 51. The removal of one of the 3/4-inch- (1.9-cm-) diameter short tubes in line with the spark plug was necessitated to restore satisfactory ignition.

Shifting the airflow distribution back to the mixing zone in model 5-G (fig. 9) resulted in smoke number of 24. It should be pointed out, however, that the incorporation of the modified nozzle shroud shown in figure 3 had a marked effect on the observed reduction in smoke number because subsequent tests with model 5-H (which was identical to model 5-G except that the standard nozzle shroud was used) resulted in an increase in smoke number to 45. These results were repeatable. The increased hole area of the modified shroud results in only a minor increase in airflow; however, the intimate contact of this air with fuel at the point of injection into the combustor apparently has a large effect on smoke formation. Similar results were reported in reference 2. The model 5-G was considered to be the best configuration investigated in this program from the standpoint of both smoke emission and overall combustor performance.

Model 6

The basic feature of the model 6 combustor series was the substitution of swirlers with larger outer diameters to increase the swirler open area. Models 6-A and 6-B (fig. 27) used a swirler with ten 70° turning vanes and an open area of 0.113 square foot (1.05×10^{-2} sq m). Models 6-A and 6-B differed only in primary zone airflow distribution. A swirler with ten 55° turning vanes and an open area of 0.113 square foot

(1.05×10^{-2} sq m) was used in models 6-C and 6-D. Model 6-D incorporated 48 5/16-inch- (0.79-cm-) diameter holes in the dome (fig. 28); otherwise, models 6-C and 6-D differed only in primary zone airflow distribution. An unsatisfactory smoke number was observed in all of these configurations.

A radial swirler with an open area of 0.055 square foot (5.11×10^{-3} sq m) was incorporated in model 6-E (fig. 29). A smoke number of 28 was recorded for this configuration.

Model 7

Model 7 was similar to model 5-G, differing mainly in the open hole geometry in the dome. Models 7-A and 7-B were identical except that model 7-A used the modified nozzle shroud (fig. 3) while model 7-B used the standard shroud. The observed smoke numbers were 16 and 69 for models 7-A and 7-B, respectively. As noticed previously with models 5-G and 5-H, the modified nozzle shroud had a marked effect on reducing smoke number. Increasing the mixing zone airflow distribution further in model 7-C did not improve the smoke number. The model 7-C combustor had very poor ignition characteristics.

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11. Turner, L. Richard; and Bogart, Donald: Constant-Pressure Combustion Charts Including Effects of Diluent Addition. NACA Rep. 937, 1949.

TABLE I. - SUMMARY OF COMBUSTOR MODIFICATIONS.

Model numbers	Description
1-A	Production combustor liner.
1-B	Identical to model 1-A except low pressure drop natural gas nozzles substituted for model 1-A duplex nozzle.
2-A	Identical to model 1-A except 54 1/4-inch (0.64-cm) holes drilled in dome (nine between each swirler at air-entry station 10).[a]
2-B	Identical to model 2-A except 41 percent of air-entry holes at station 5 were blocked off.
2-C	Identical to model 2-B except 30 3/8-inch (0.952-cm) holes added at station 1; blocked off all holes at stations 3 and 4 and 24 percent of holes at station 5.
2-D	Identical to model 2-C except 12-gallon-per-hour (45.6-liter/hr) simplex nozzle substituted for model 1-A duplex nozzles and larger swirler substituted for model 1-A swirler.
2-E	Identical to model 2-D except blocked off all holes at stations 1, 2, 3, 4, 6, 7, and 8; station 5 entirely unblocked.
2-F	Identical to model 2-E except all holes unblocked.
2-G	Identical to model 2-F except 41 1/4-inch (0.64-cm) holes added to dome at station 15; blocked off all holes at stations 1, 2, 3, and 4.
3-A	Identical to model 1-A except 30 3/8-inch (0.952-cm) holes added at station 1.
3-B	Identical to model 3-A except blocked off all holes at stations 3 and 4, and 24 percent of holes at station 5.
3-C	Identical to model 3-B except 30 3/8-inch (0.952-cm) holes added at station 2; section of inner liner containing stations 6, 7, and 8 was cut off and section containing station 4 was fastened at forward end of liner.
3-D	Identical to model 3-C except inner liner restored to original design; 13.5-gallon-per-hour (51.3×10^3-cc/hr) simplex nozzle substituted for model 1-A duplex nozzle.
4-A	Identical to model 1-A except six 1.01-square-inch (6.53-sq cm) slots added to dome at station 10; blocked off all holes at stations 1, 2, 3, 4, 6, 7, and 8.
4-B	Identical to model 4-A except deflector plates installed inside dome behind six slots; 30 3/8-inch (0.952-cm) holes added at station 1; 30 3/8-inch (0.952-cm) holes added to station 2; 12 3/8-inch (0.952-cm) holes added at station 14; blocked off holes at stations 3 and 4, and 24 percent of hole at station 5 (all other stations were unblocked).
4-C	Identical to model 4-B except $10\frac{7}{16}$-inch (26.5-cm) inside diameter shroud installed; unblocked all air-entry stations.
4-D	Identical to model 4-B except blocked off all holes at stations 2, 3, and 4 (all other stations were unblocked).
4-E	Identical to model 4-D except removed deflector plates inside dome; 41 1/4-inch (0.64-cm) holes added to dome at station 15.
4-F	Identical to model 4-E except model A-1 duplex nozzle operation modified by passing high pressure air through primary.
4-G	Identical to model 4-E except six 1/2-inch- (1.27-cm-) wide V-gutters installed upstream of slots in dome; blocked off all holes at stations 1, 2, 3, and 4; nozzle shroud slot area increased.
4-H	Identical to model 4-G except six 1/2-inch (1.27-cm) holes added at station 12 (in-line with swirlers); blocked all holes at stations 2, 3, and 4.
5-A	Identical to model 1-A except six 1.01-square-inch (1.53-sq cm) slots added to dome at station 10; deflector plates installed inside dome behind slots.
5-B	Identical to model 5-A except deflector plates removed and punched plate (30 percent open area) installed upstream of each slot.
5-C	Identical to model 5-A except deflector plates reduced to 1/2-inch (1.27-cm) width; blocked off all holes at stations 1, 2, 3, and 4; installed model 4-G nozzle shroud.
5-D	Identical to model 5-C except removed 1/2-inch- (1.27-cm-) wide deflector plates; installed six 1/2-inch- (1.27-cm-) wide V-gutters upstream of each slot in dome; blocked all holes at stations 2, 3, and 4; ten 1/2-inch (1.27-cm) holes added at station 1.
5-E	Identical to model 5-D except blocked all holes at stations 1, 2, 3, and 4; added six 3/4-inch- (1.9-cm-) short tubes at station 13 (in-line with swirler); removed model 4-G nozzle shroud and reinstalled standard nozzle shroud.
5-F	Identical to model 5-D except 3/4-inch- (1.9-cm-) short tube at station 13 in-line with spark plug blocked off; unblocked stations 1, 2, 3, and 4.
5-G	Identical to model 5-F except blocked off all holes in stations 2, 3, and 4; blocked off nine out of ten 1/2-inch (1.27-cm) holes added at station 1 (1/2-inch or 1.27-cm hole in-line with spark plug left open); installed model 4-G nozzle shroud.
5-H	Identical to model 5-G except standard nozzle shroud installed.
6-A	Identical to model 1-A except standard swirler replaced by larger swirler with 70° turning vanes; installed model 4-G nozzle shroud.
6-B	Identical to model 6-A except blocked off all holes at stations 1, 2, 3, and 4.
6-C	Identical to model 6-B except large swirler with 55° turning vanes installed.
6-D	Identical to model 6-C except blocked off all holes at stations 2, 3, and 4 only; 48 5/16-inch (0.79-cm) holes added at station 10 (eight between each swirler).
6-E	Identical to model 6-D except radial swirlers installed; blocked off 48 5/16-inch (0.79-cm) holes at station 10.
7-A	Identical to model 1-A except five 3/4-inch- (1.9-cm-) short tubes added at station 13 (in-line with each swirler except one near spark plug); 48 1/4-inch (0.64-cm) holes added at station 10 (eight between each swirler); installed model 4-G nozzle shroud.
7-B	Identical to model 7-A except standard nozzle shroud installed.
7-C	Identical to model 7-A except six additional 3/4-inch- (1.9-cm-) short tubes added at station 13 (straddling swirlers).

[a]Positions of air-entry stations are shown in fig. 7.

TABLE II. - AIR-ENTRY HOLE

Model number	1	2	3	4	5	6	7	8
						Hole area at each air-entry station		
1-A	0.008 (7.432)	0.017 (15.794)	0.011 (10.219)	0.011 (10.219)	0.041 (38.090)	0.005 (4.645)	0.005 (4.645)	0.005 (4.645)
1-B	.008 (7.432)	.017 (15.794)	.011 (10.219)	.011 (10.219)	.041 (38.090)	.005 (4.645)	.005 (4.645)	.005 (4.645)
2-A	.008 (7.432)	.017 (15.794)	.011 (10.219)	.011 (10.219)	.041 (38.090)	.005 (4.645)	.005 (4.645)	.005 (4.645)
2-B	.008 (7.432)	↓	.011 (10.219)	.011 (10.219)	.024 (22.297)	↓	↓	↓
2-C	.031 (28.800)	↓	0 (0)	0 (0)	.031 (28.800)	↓	↓	↓
2-D	.031 (28.800)	↓	↓	↓	.031 (28.800)	↓	↓	↓
2-E	0 (0)	0 (0)	↓	↓	.041 (38.090)	0 (0)	0 (0)	0 (0)
2-F	.031 (28.800)	.017 (15.794)	.011 (10.219)	.011 (10.219)	↓	.005 (4.645)	.005 (4.645)	.005 (4.645)
2-G	0 (0)	0 (0)	0 (0)	0 (0)	↓	.005 (4.645)	.005 (4.645)	.005 (4.645)
3-A	.031 (28.800)	.017 (15.794)	.011 (10.219)	.011 (10.219)	.041 (38.090)	.005 (4.645)	.005 (4.645)	.005 (4.645)
3-B	↓	.017 (15.794)	0(0)	0(0)	.031 (28.800)	.005 (4.645)	.005 (4.645)	.005 (4.645)
3-C	↓	.040 (37.161)	.011 (10.219)	.011 (10.219)	.041 (38.090)	0(0)	0(0)	0(0)
3-D	↓	.040 (37.161)	.011 (10.219)	.011 (10.219)	.041 (38.090)	.005 (4.645)	.005 (4.645)	.005 (4.645)
4-A	0 (0)	0 (0)	0 (0)	0 (0)	.041 (38.090)	0 (0)	0 (0)	0 (0)
4-B[c]	.031 (28.800)	.040 (37.161)	0 (0)	0 (0)	.031 (28.800)	.005 (4.645)	.005 (4.645)	.005 (4.645)
4-C[c,d]	↓	.040 (37.161)	.011 (10.219)	.011 (10.219)	.041 (38.090)	↓	↓	↓
4-D[c]	↓	0 (0)	0 (0)	0 (0)	↓	↓	↓	↓
4-E	↓	↓	↓	↓	↓	↓	↓	↓
4-F	↓	↓	↓	↓	↓	↓	↓	↓
4-G[e]	0 (0)	↓	↓	↓	↓	↓	↓	↓
4-H	.031 (28.800)	↓	↓	↓	↓	↓	↓	↓
5-A	.008 (7.432)	.017 (15.794)	.011 (10.219)	.011 (10.219)	.041 (38.090)	.005 (4.645)	.005 (4.645)	.005 (4.645)
5-B[f]	.008 (7.432)	.017 (15.794)	.011 (10.219)	.011 (10.219)	↓	↓	↓	↓
5-C[g]	0 (0)	0 (0)	0 (0)	0 (0)	↓	↓	↓	↓
5-D[e]	.022 (20.439)	↓	↓	↓	↓	↓	↓	↓
5-E	0 (0)	↓	↓	↓	.005 (4.645)	↓	↓	↓
5-F	.022 (20.439)	.017 (15.794)	.011 (10.219)	.011 (10.219)	.041 (38.090)	↓	↓	↓
5-G	.009 (8.361)	0 (0)	0 (0)	0 (0)	↓	↓	↓	↓
5-H	0 (0)	0 (0)	0 (0)	0 (0)	↓	↓	↓	↓
6-A	.008 (7.4323)	.017 (15.794)	.011 (10.219)	.011 (10.219)	.041 (38.090)	.005 (4.645)	.005 (4.645)	.005 (4.645)
6-B	0 (0)	0 (0)	0 (0)	0 (0)	↓	↓	↓	↓
6-C	.008 (7.4323)	.017 (15.794)	.011 (10.219)	.011 (10.219)	↓	↓	↓	↓
6-D	↓	0 (0)	0 (0)	0 (0)	↓	↓	↓	↓
6-E	↓	0 (0)	0 (0)	0 (0)	↓	↓	↓	↓
7-A	.008 (7.4323)	.017 (15.794)	.011 (10.219)	.011 (10.219)	.041 (38.090)	.005 (4.645)	.005 (4.645)	.005 (4.645)
7-B	↓	↓	↓	↓	↓	↓	↓	↓
7-C	↓	↓	↓	↓	↓	↓	↓	↓

[a]Swirler turning angle, 45°.
[b]Ignoring projected blockage of deflector plate.
[c]Deflector plates installed behind slots at station 10.
[d]$10\frac{7}{16}$-in. (26.5-cm) I.D. shroud installed.
[e]1/2-in.- (1.27-cm-) wide V-gutter installed upstream of each of six slots in dome.
[f]30 percent open area punched plate installed upstream of each of six slots in dome.
[g]1/2-in. - (1.27-cm-) wide deflector plates installed behind slots at station 10.
[h]Subtracting projected blockage of V-gutters (baffles).
[i]Swirler turning angle, 70°.
[j]Swirler turning angle, 55°.
[k]Radial swirler installed.

DISTRIBUTION OF EACH COMBUSTOR MODEL.

Station								
9	10	11 (Swirler)	12	13	14	15	Fuel nozzle	Nozzle air shroud
(excluding film cooling openings, sq ft (sq cm))								
0.017 (15.794)	0 (0)	0.046 (42.736)	0 (0)	0 (0)	0 (0)	0 (0)	Duplex	Standard
.017 (15.794)	0 (0)	.046 (42.736)	0 (0)	0 (0)	0 (0)	0 (0)	Gas	Standard
.017 (15.794)	.018 (16.723)	.046 (42.736)	0 (0)	0 (0)	0 (0)	0 (0)	Duplex	Standard
↓	↓	↓	↓	↓	↓	↓	↓	↓
		.069 (64.103)[a]					Simplex	None
↓	↓	↓	↓	↓	↓	.014 (13.007)	↓	↓
..017 (15.794)	0 (0)	.046 (42.736)	0 (0)	0 (0)	0 (0)	0 (0)	Duplex	Standard
.017 (15.794)	↓	↓	↓	↓	↓	↓	↓	↓
0 (0)								
.017 (15.794)							Simplex	None
.017 (15.794)	.042 (39.019)[b]	.046 (42.736)	0 (0)	0 (0)	0 (0)	0 (0)	Duplex	Standard
↓	.042 (39.019)[b]	↓	↓	↓	.009 (8.361)	↓	↓	↓
						.014 (13.007)		
						↓	Air atomizer	
							Duplex	Modified
	.042 (39.019)		.008 (7.432)				Duplex	Modified
.017 (15.794)	.042 (39.019)	.046 (42.736)	0 (0)	0 (0)	0 (0)	0 (0)	Duplex	Standard
↓	↓	↓	↓	↓	↓	↓	↓	Standard
								Modified
	.014 (13.007)[h]							Modified
	.014 (13.007)[h]			.0155 (14.400)			Duplex	Standard
	.014 (13.007)			.0129 (11.984)			↓	Standard
	↓			↓				Modified
								Standard
.017 (15.794)	0 (0)	.1132 (105.166)[i]	0 (0)	0 (0)	0 (0)	0 (0)	Duplex	Modified
↓	↓	.1132 (105.166)[i]	↓	↓	↓	↓	↓	↓
		.1132 (105.166)[j]						
	.0255 (23.690)	.1132 (105.166)[j]						
	0 (0)	.055 (51.097)[k]						
.017 (15.794)	.0164 (15.236)	.046 (42.736)	0 (0)	.0129 (11.984)	0 (0)	0 (0)	Duplex	Modified
↓	↓	↓	↓	.0129 (11.984)	↓	↓	↓	Standard
				.0284 (26.385)				Modified

TABLE III. - SUMMARY OF OVERALL PERFORMANCE OF EACH COMBUSTOR MODEL

Model number	Total air-entry area (a)		Primary air-entry area (b)		Ratio of primary to total air-entry area, percent	Mixing zone air-entry area (c)		Ratio of mixing zone to total air-entry area, percent (c)	Smoke number	Combustor efficiency, η_c, percent	Combustor total pressure loss, $\Delta P/P$, percent	Exit temperature pattern factor
	sq ft	sq cm	sq ft	sq cm		sq ft	sq cm					
1-A	0.241	223.9	0.059	54.8	24.5	0.046	42.7	19.1	64	99.6	1.5	0.15
1-B	.241	223.9	.059	54.8	24.5	.046	42.7	19.1	0	102	1.7	.39
2-A	.259	240.6	.077	71.5	29.7	.064	59.5	24.7	70	97.9	1.5	.16
2-B	.242	224.8	.077	71.5	31.8	.064	59.5	26.4	67	97.9	1.5	.35
2-C	.250	232.3	.100	92.9	40.0	.064	59.5	25.6	49	98.9	1.4	.37
2-D	.273	253.6	.123	114.3	45.1	.087	80.8	31.9	24-32	[d]97.3	1.4	.31
2-D	.273	253.6	.123	114.3	45.1	.087	80.8	31.9	60	[e]98.4	1.3	.33
2-E	.220	204.4	.087	80.8	39.5	.087	80.8	39.5	33	98.0	1.4	.52
2-F	.305	283.4	.123	114.3	40.3	.087	80.8	28.5	38	95.7	1.1	.27
2-G	.249	231.3	.106	98.5	42.6	.101	93.8	40.6	38	96.0	1.3	.32
3-A	.264	245.3	.082	76.2	31.1	.046	42.7	17.4	57	97.3	1.3	.29
3-B	.232	215.5	.082	76.2	35.3	.046	42.7	19.8	52	97.7	1.7	.24
3-C	-----	-----	-----	-----	----	-----	----	----	38	99.8	1.5	.66
3-D	.287	266.6	.082	76.2	28.6	.046	42.7	16.0	68	99.2	1.1	.50
4-A	.221	205.3	.088	81.8	39.8	.088	81.8	39.8	38	99.1	1.3	.31
4-B	.306	284.3	.133	123.6	43.5			28.8	20	98.3	1.2	.32
4-C	.338	314.0	.133	123.6	39.4			26.0	11	100.2	2.2	.50
4-D	.276	256.4	.133	123.6	48.3			31.8	19	90.1	1.5	.45
4-E	.290	269.4	.147	136.6	50.7	.102	94.8	35.2	61	94.0	1.0	.33
4-F	.290	269.4	.147	136.6	50.7			35.2	57	97.0	1.0	.31
4-G	.259	240.6	.116	107.3	44.8			39.4	47	96.8	1.4	.49
4-H	.298	276.9	.155	144.0	52.0			34.2	57	96.9	1.3	.38
5-A	.283	262.9	.101	93.8	35.7	.088	81.8	31.1	14	99.2	1.4	.24
5-B	.283	262.9	.101	93.8	35.7	.088	81.8	31.1	50	97.5	1.4	.29
5-C	.236	219.3	.093	86.4	39.4	.088	81.8	37.3	45	97.5	1.6	.25
5-D	.230	213.7	.087	80.8	37.8	.044	40.9	19.2	48	95.6	1.5	.33
5-E	.224	208.1	.081	75.3	36.2	.076	70.6	33.9	27	95.0	1.6	.32
5-F	.282	262.0	.100	92.9	35.5	.073	67.8	25.9	51	97.3	1.1	.28
5-G	.230	213.7	.087	80.8	37.8	.073	67.8	31.8	24	94.7	1.5	.30
5-H	.230	213.7	.087	80.8	37.8	.073	67.8	31.8	45	96.3	1.4	.35
6-A	.308	286.1	.126	117.1	40.9	.113	105.0	36.7	79	98.0	1.4	.43
6-B	.261	242.5	.118	109.6	45.2	.113	105.0	43.3	82	101.0	1.8	.28
6-C	.308	286.1	.126	117.1	40.9	.113	105.0	36.7	55	97.9	1.1	.55
6-D	.295	274.1	.152	141.2	51.5	.139	129.1	47.1	70	93.6	1.1	.46
6-E	.211	196.0	.068	63.2	32.2	.055	51.1	26.1	28	97.2	1.4	.28
7-A	.270	250.8	.088	81.8	32.6	.075	69.7	27.8	19	98.6	1.4	.27
7-B	.270	250.8	.088	81.8	32.6	.075	69.7	27.8	69	98.8	1.4	.40
7-C	.285	264.8	.103	95.7	36.1	.090	83.6	31.6	23	95.0	1.2	.38

[a]Including swirler, dome holes, and liner dilution and film cooling openings.

[b]Including stations 11 (swirler); 10 and 15 (dome holes); 1, 12, and 13 (outer liner openings); and 6 and 14 (inner liner openings) but excluding film cooling openings.

[c]Including stations 11 (swirler); 10 and 15 (dome holes); and 13 (outer liner openings) but excluding film cooling openings.

[d]12 gal/hr (45.6×10^3 cc/hr).

[e]13.5 gal/hr (51.3×10^3 cc/hr).

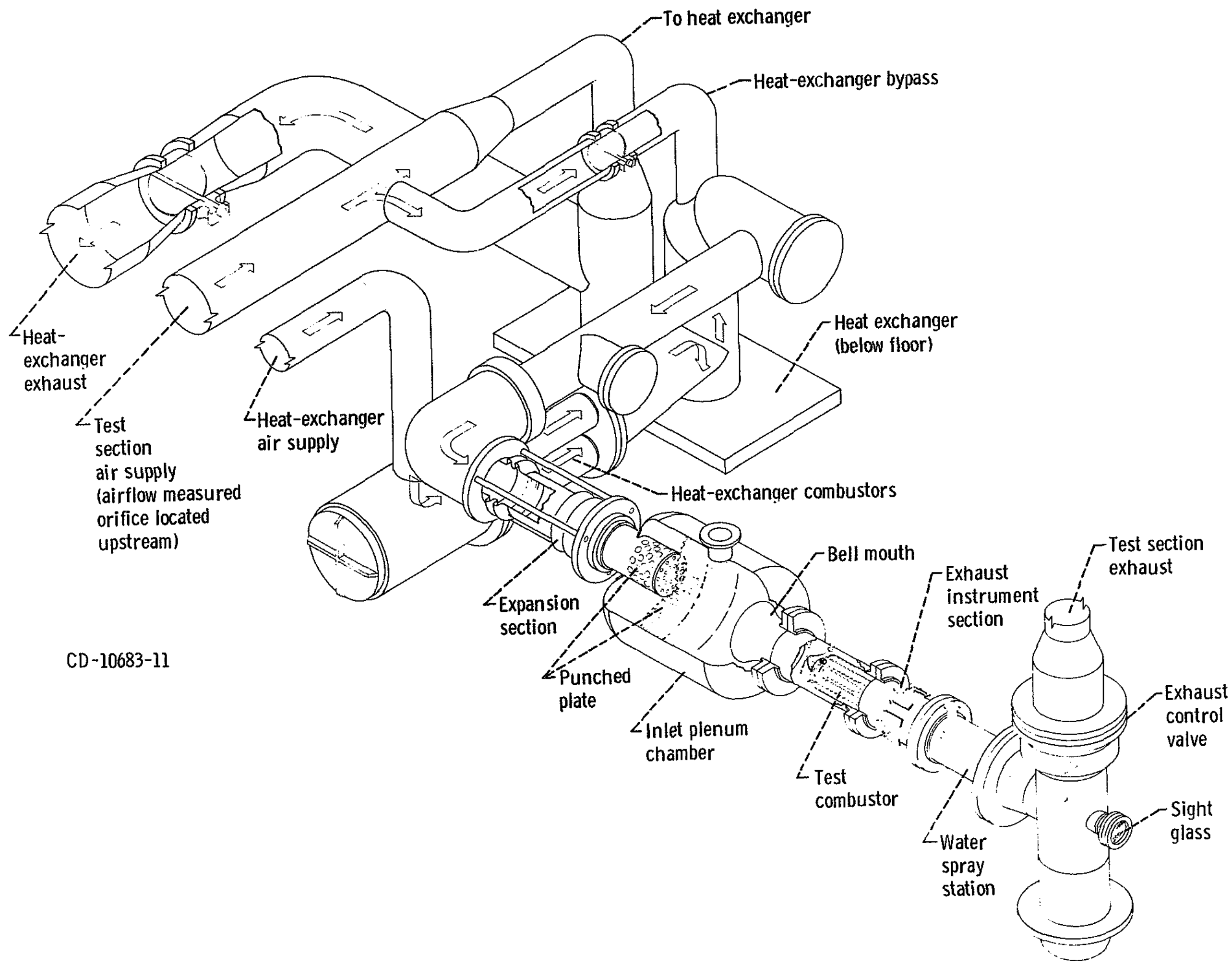
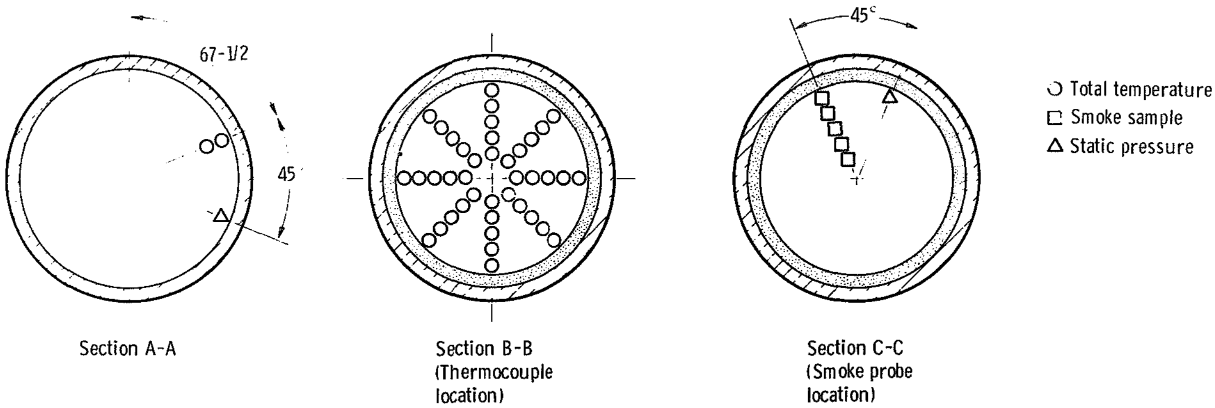
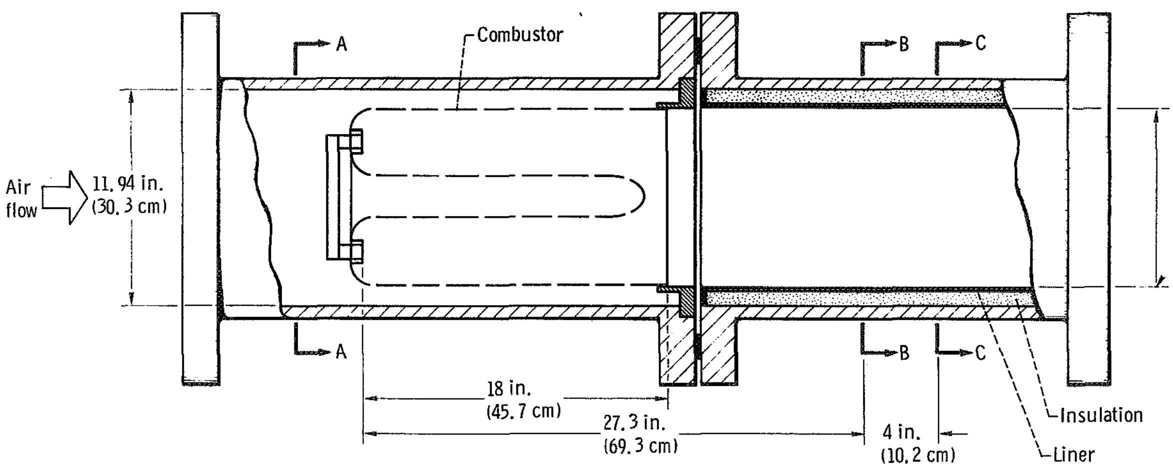


Figure 1. - Test installation.



(a) Instrumentation stations.



(b) Location of instrumentation at each station.

Figure 2. - Combustor test duct.

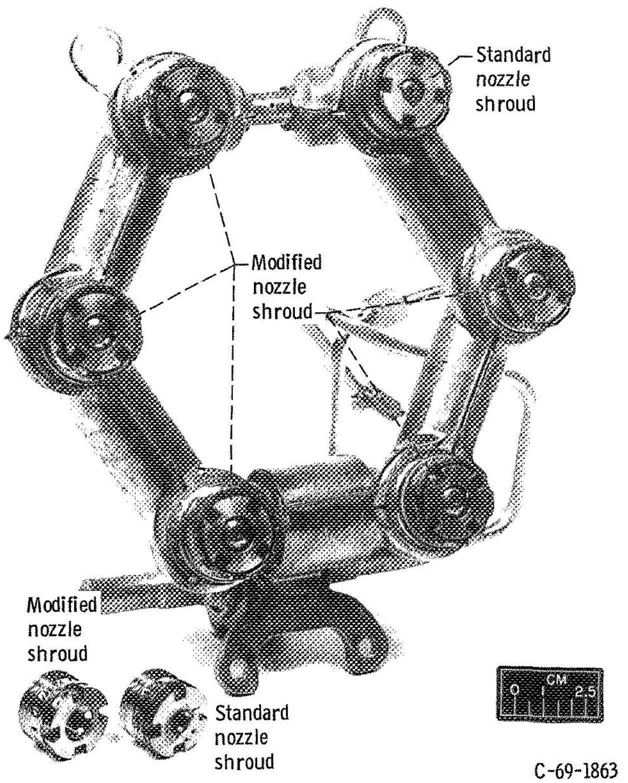


Figure 3. - Fuel nozzle manifold for test combustor showing installation of either standard or modified nozzle shroud.

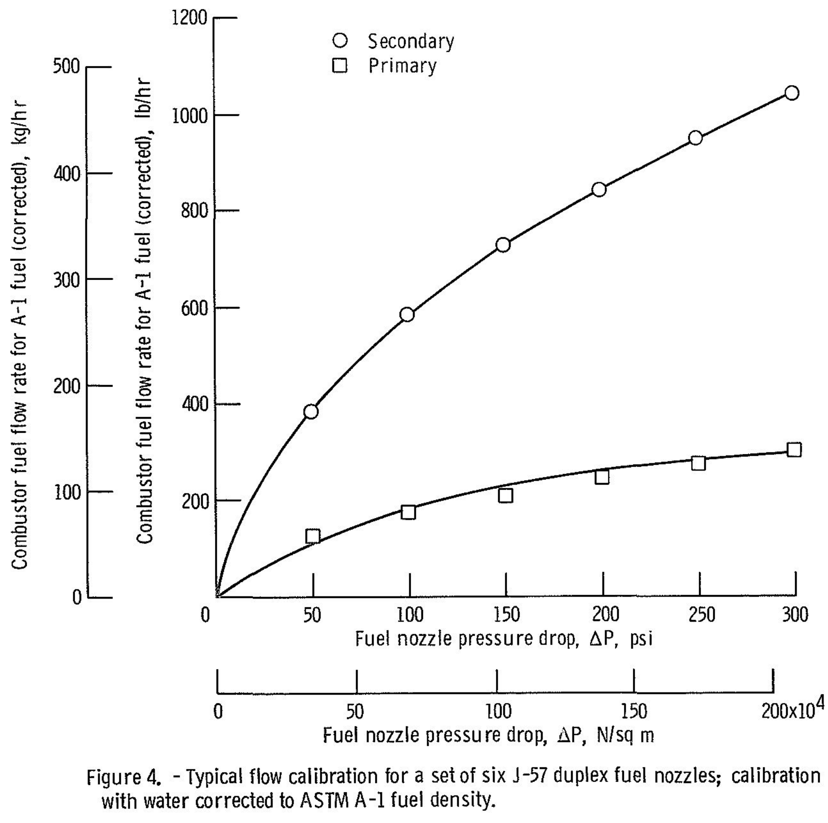


Figure 4. - Typical flow calibration for a set of six J-57 duplex fuel nozzles; calibration with water corrected to ASTM A-1 fuel density.

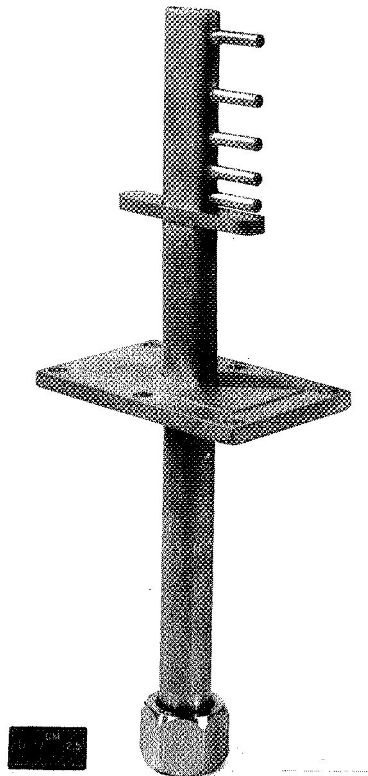


Figure 5. - Smoke sampling probe.

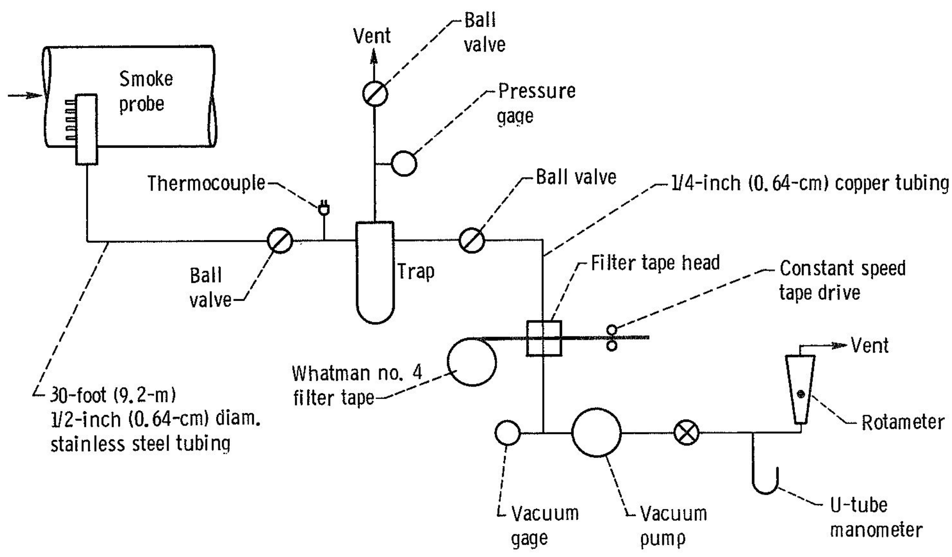


Figure 6. - Schematic drawing of smoke sampling system.

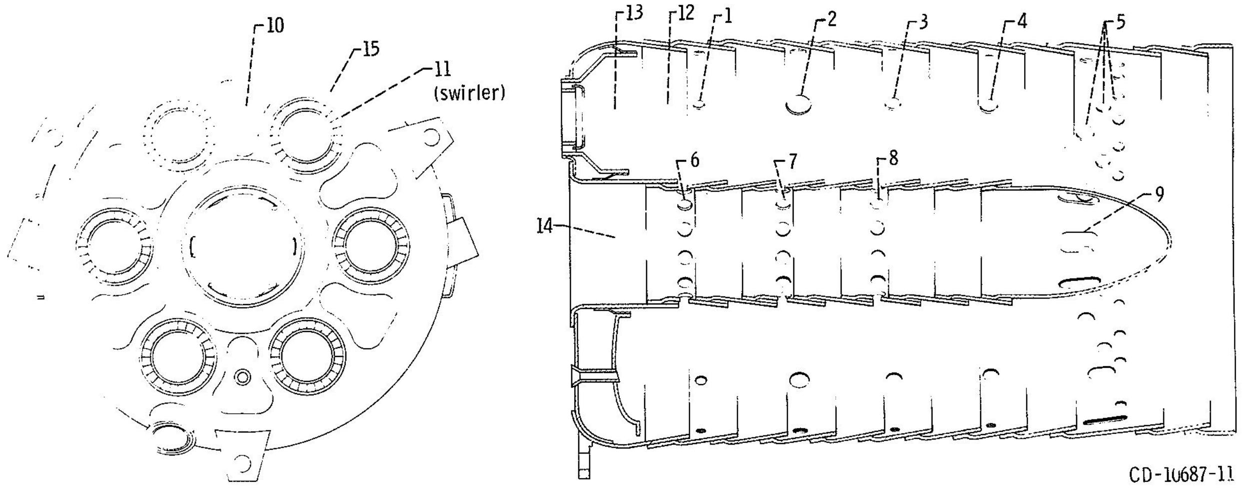
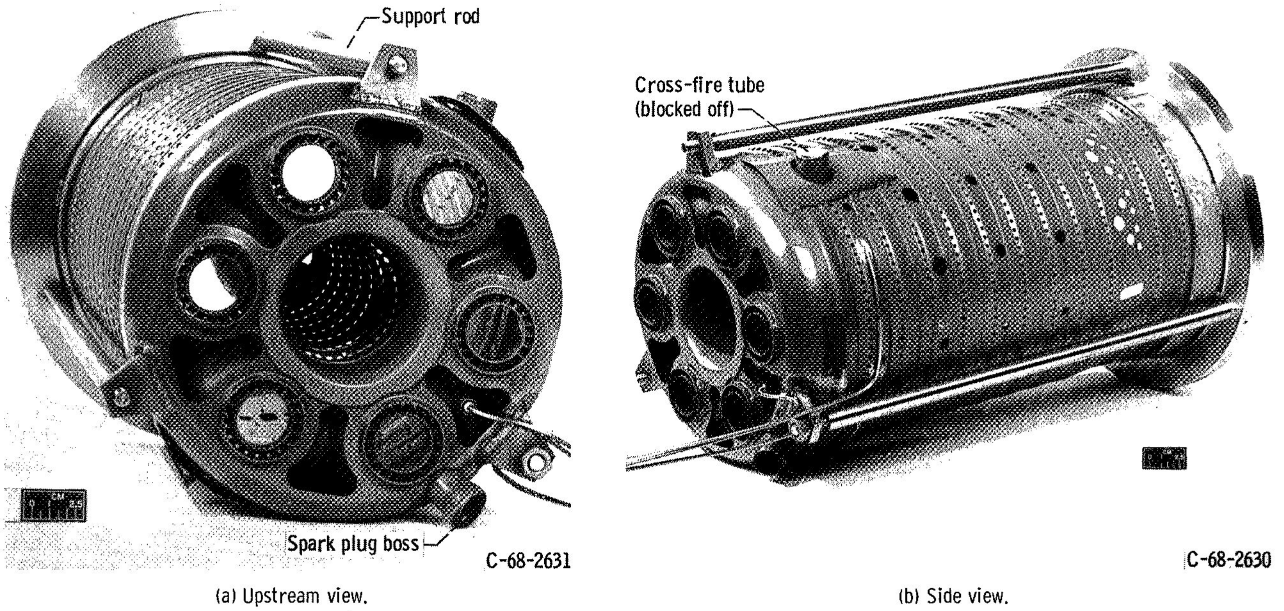


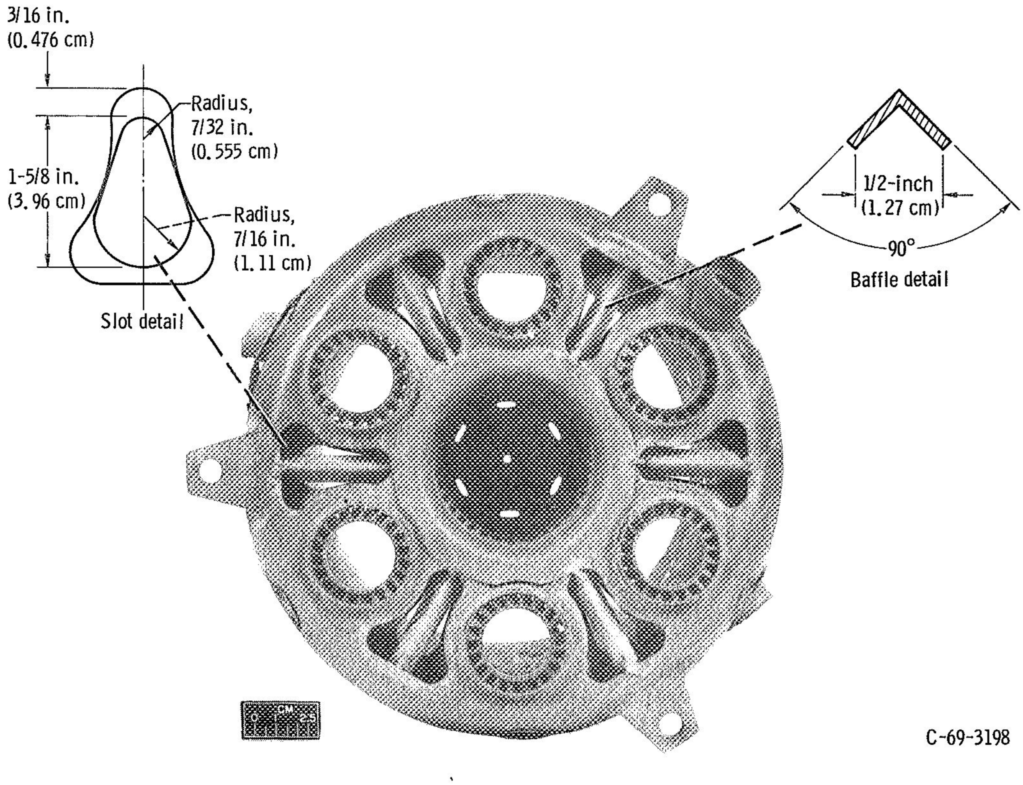
Figure 7. - Location of combustor air-entry stations.



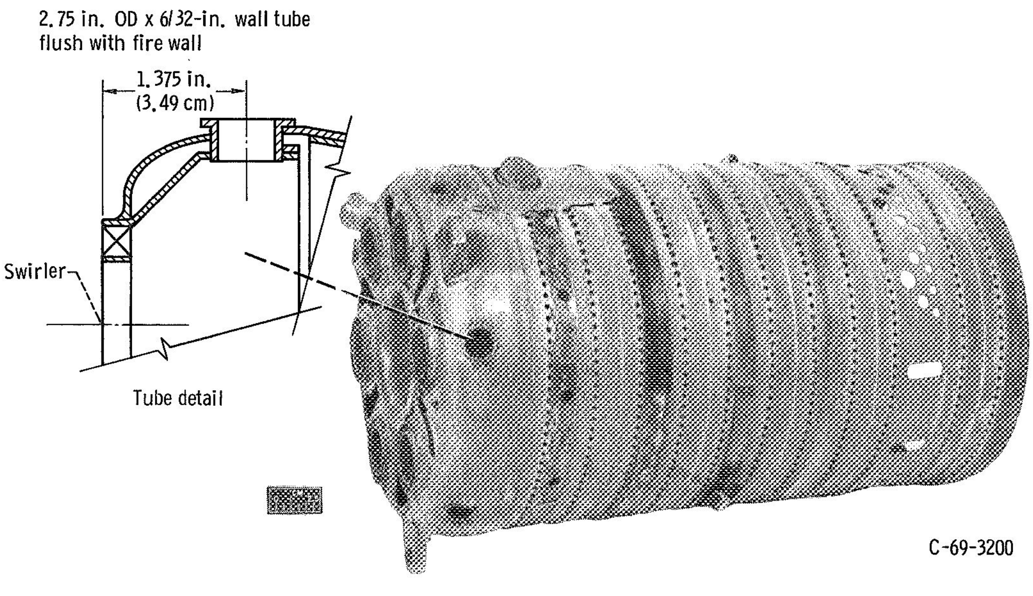
(a) Upstream view.

(b) Side view.

Figure 8. - Model 1-A.



(a) Upstream view.



(b) Side view.

Figure 9. - Model 5-G.

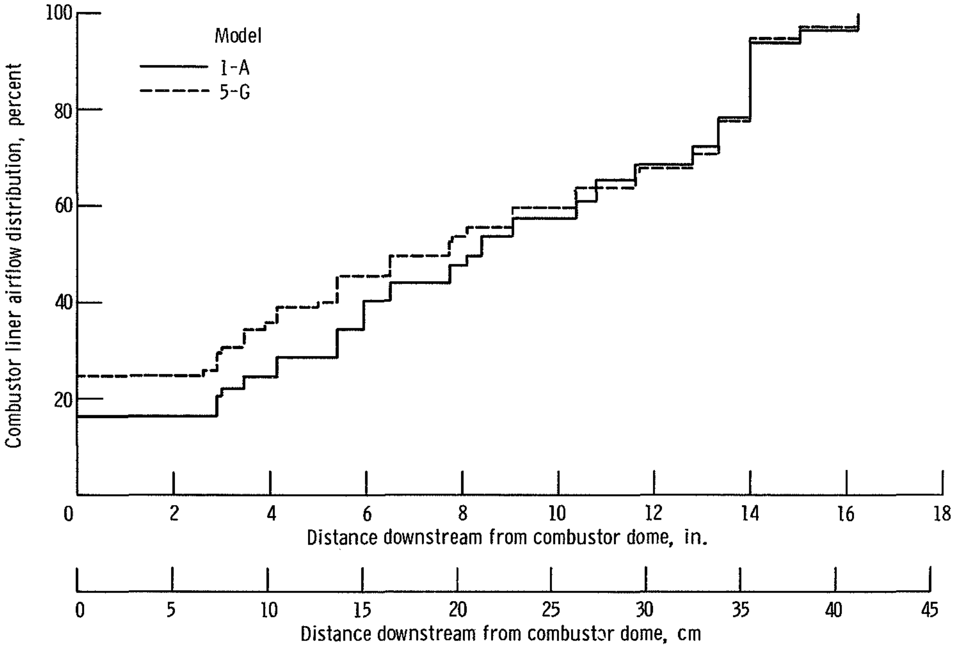


Figure 10. - Comparison of combustor liner airflow distributions for models 1-A and 5-G. Combustor inlet total pressure, 181 psia (12.3 atm); inlet total temperature, 600° F (589 K); reference velocity, 54 feet per second (16.5 m/sec); fuel-air ratio, 0.013.

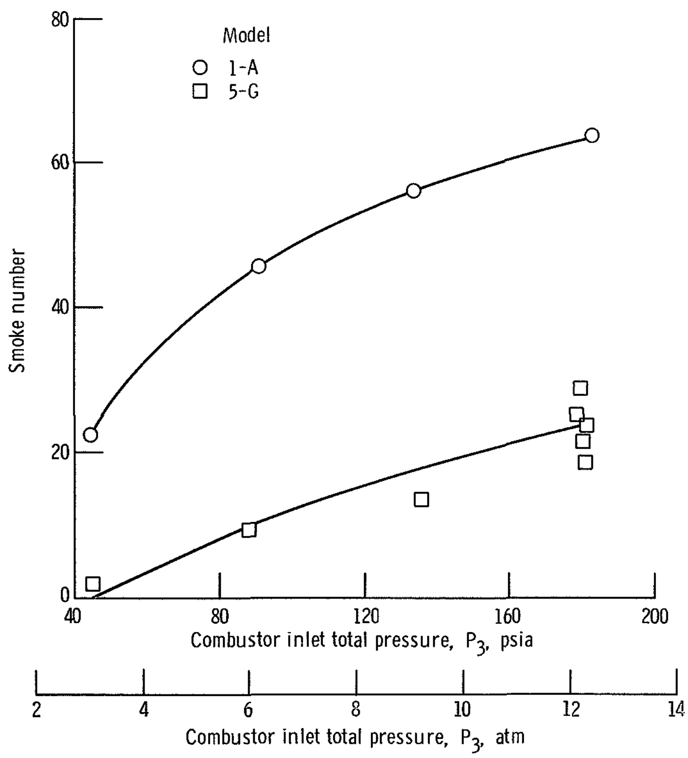


Figure 11. - Variation of smoke number with combustor inlet total pressure for models 1-A and 5-G. Combustor inlet total temperature, 600° F (589 K); combustor reference velocity, 54 feet per second (16.5 m/sec); fuel-air ratio, 0.013.

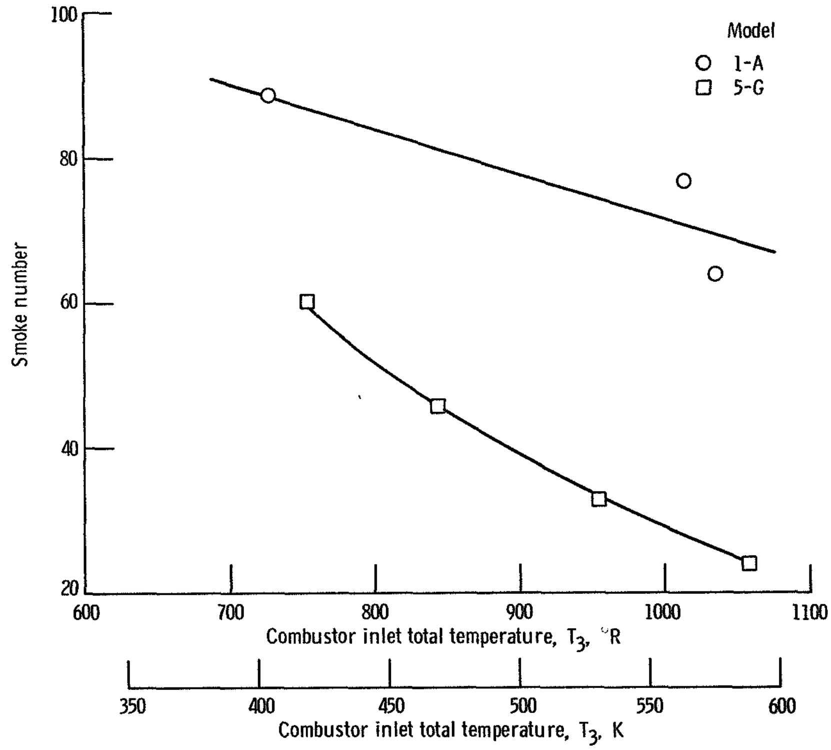


Figure 12. - Variation of smoke number with combustor inlet total temperature for models 1-A and 5-G. Combustor inlet total pressure, 181 psia (12.3 atm); reference velocity, 54 feet per second (16.5 m/sec); fuel-air ratio, 0.013.

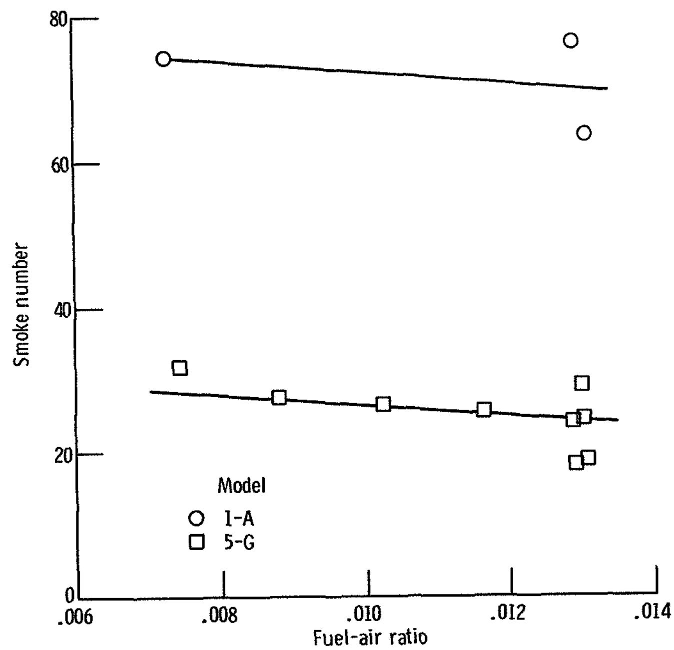


Figure 13. - Variation of smoke number with fuel-air ratio for models 1-A and 5-G. Combustor inlet total pressure, 181 psia (12.3 atm); inlet total temperature, 600° F (589 K); reference velocity, 54 feet per second (16.5 m/sec).

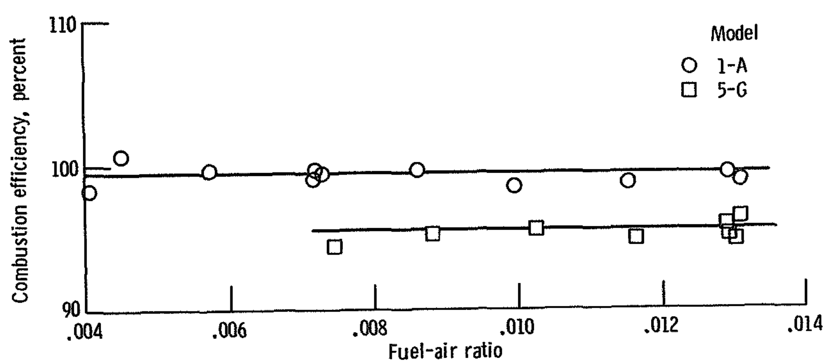


Figure 14. - Variation of combustion efficiency with fuel-air ratio for models 1-A and 5-G. Combustor inlet total pressure, 181 psia (12.3 atm); inlet total temperature, 600° F (589 K); reference velocity, 54 feet per second (16.5 m/sec).

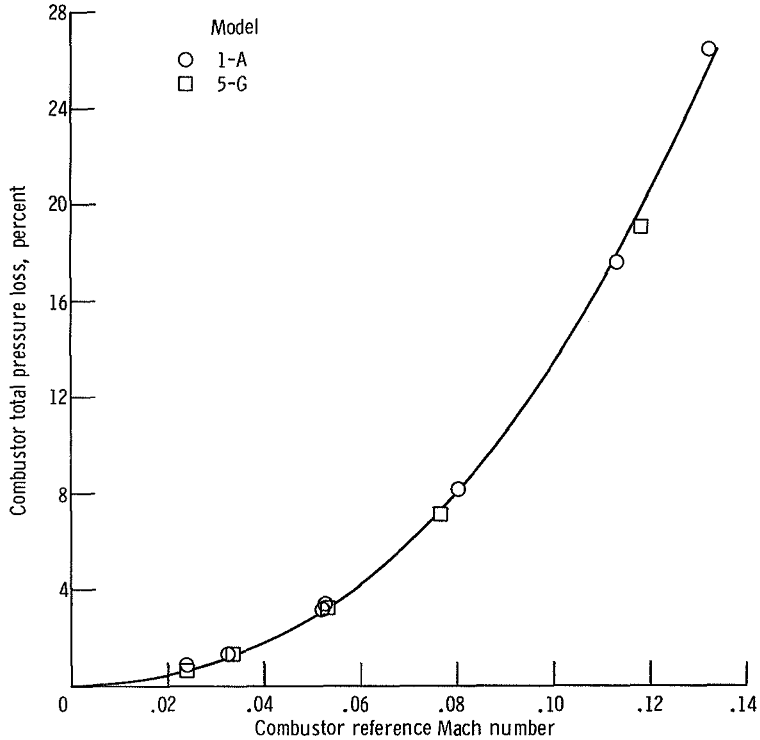
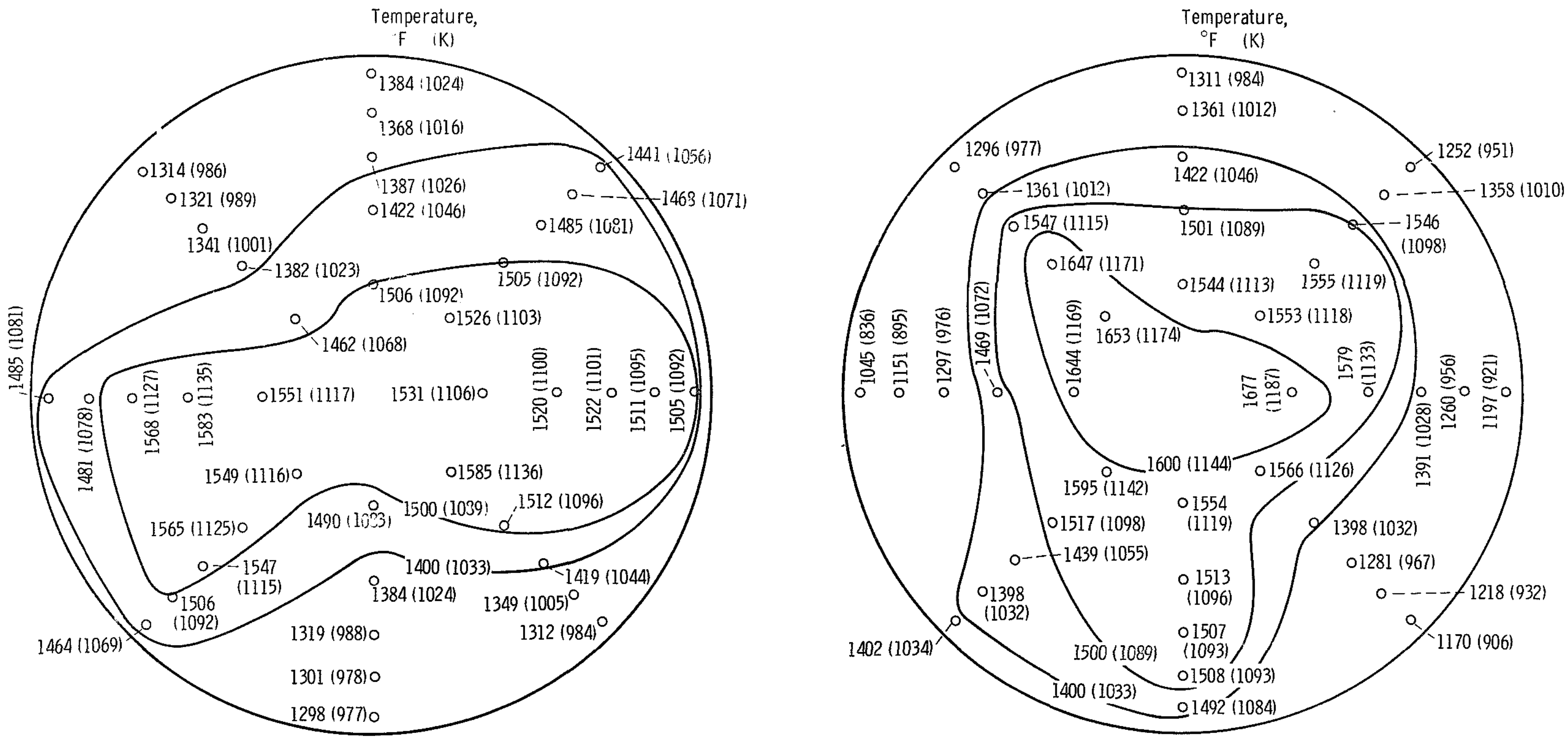


Figure 15. - Variation of combustor isothermal total pressure loss with reference Mach number for models 1-A and 5-G.



(a) Model 1-A: exit temperature pattern factor, 0.15.

(b) Model 5-G; exit temperature pattern factor, 0.30.

Figure 16. - Combustor exit temperature contours for models 1-A and 5-G. Inlet total pressure, 181 psia (12.3 atm); inlet total temperature, 600 F (589 K); reference velocity, 54 feet per second (16.5 m/sec); fuel-air ratio, 0.013.

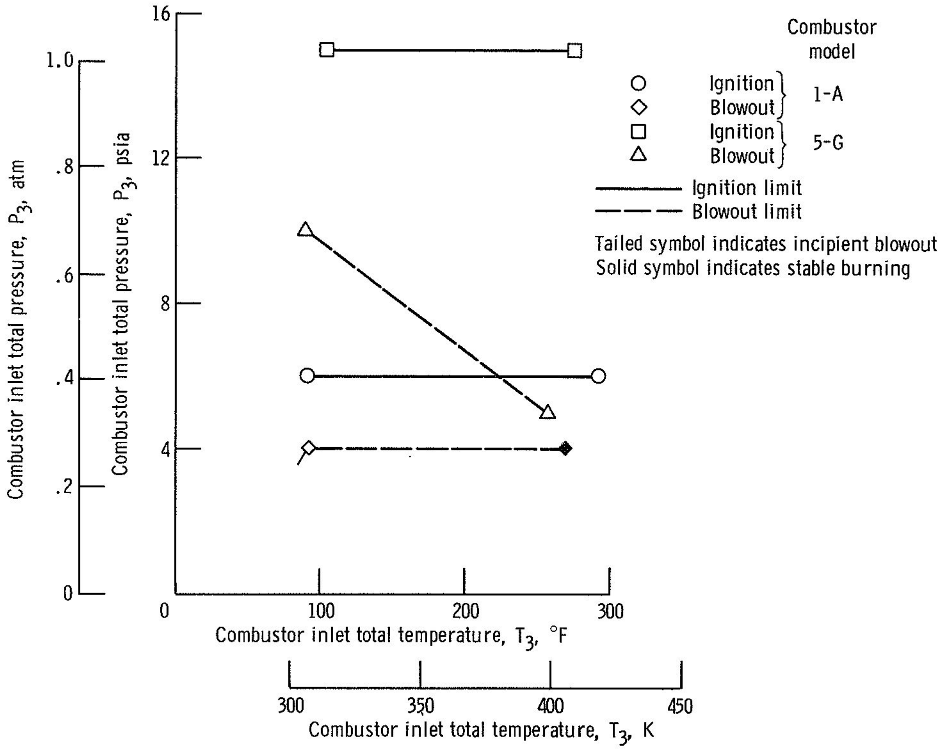
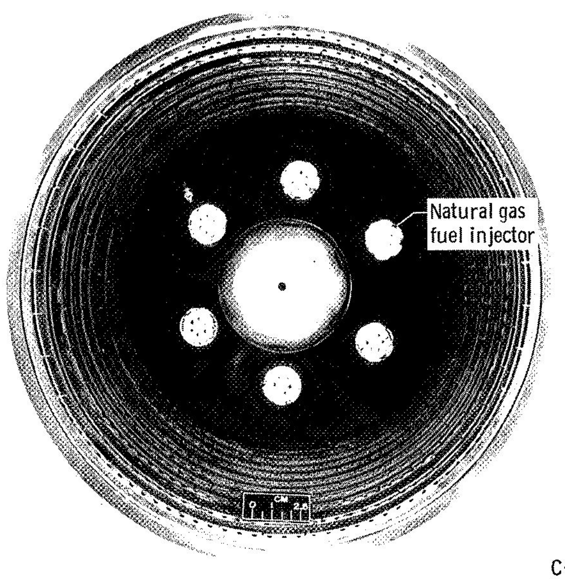
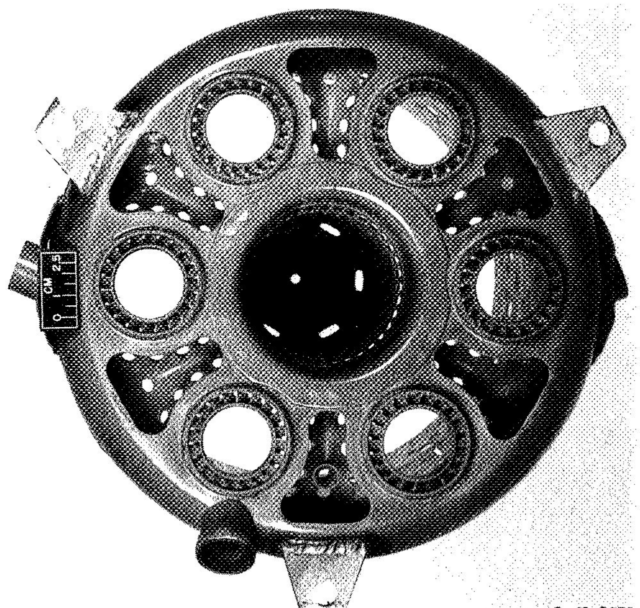


Figure 17. - Ignition and blowout limits for models 1-A and 5-G. Reference Mach number, 0.05; fuel-air ratio, 0.02.



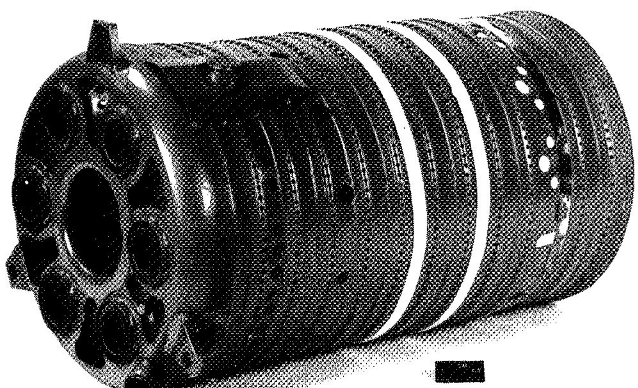
C-68-3269

Figure 18. - Model 1-B; view of inner surface of combustor dome (looking upstream).



C-68-2951

Figure 19. - Model 2-A; view of combustor dome (looking downstream).



C-68-3723

Figure 20. - Model 2-C; side view.

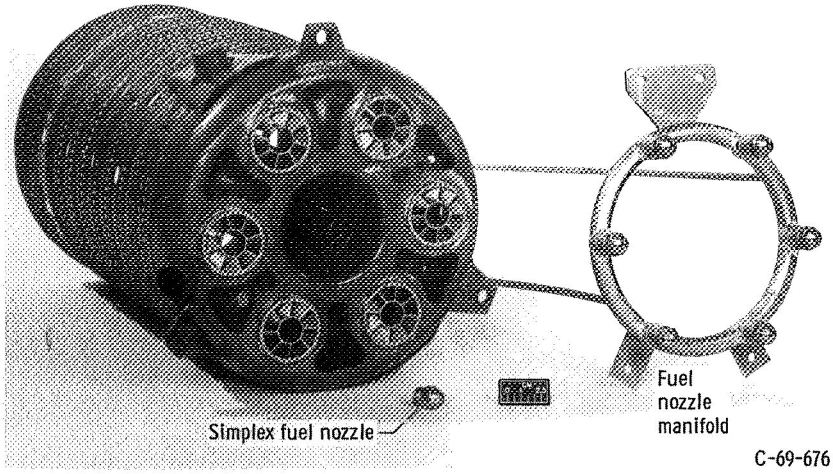


Figure 21. - Model 2-D; view of combustor dome (looking downstream).

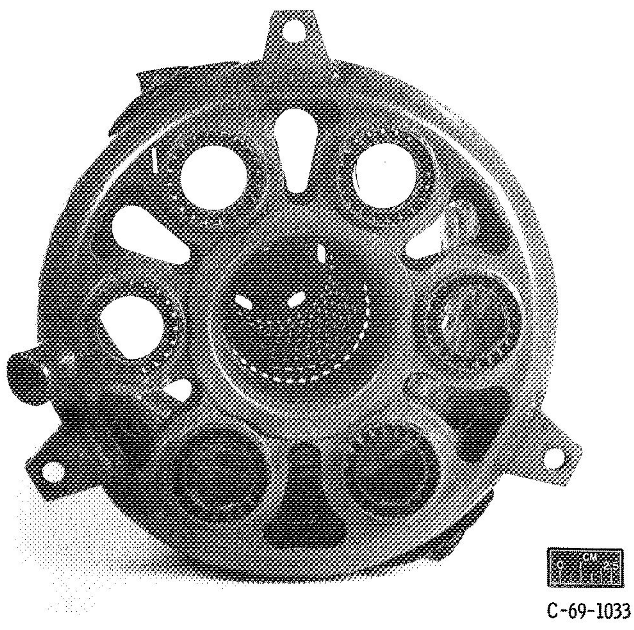


Figure 22. - Model 4-A; view of combustor dome (looking downstream).

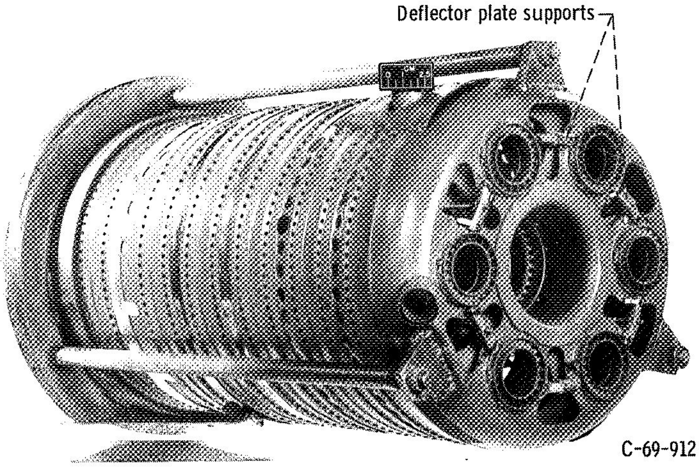


Figure 23. - Model 4-B; side view.

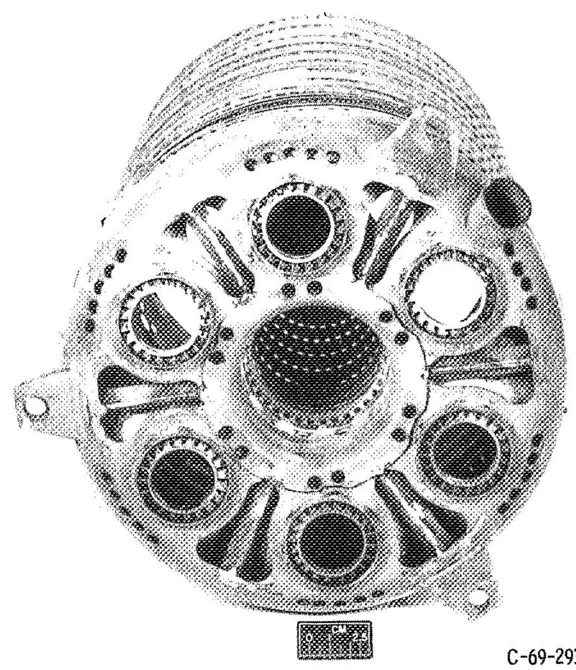


Figure 24. - Model 4-G; view of combustor dome (looking downstream).

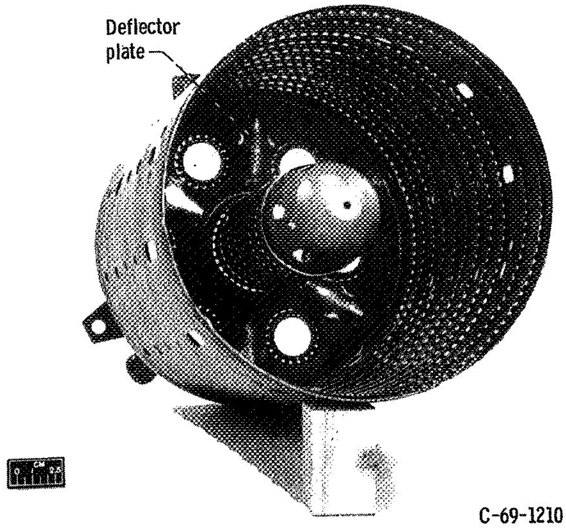


Figure 25. - Model 5-A; view of inner surface of combustor dome (looking upstream).

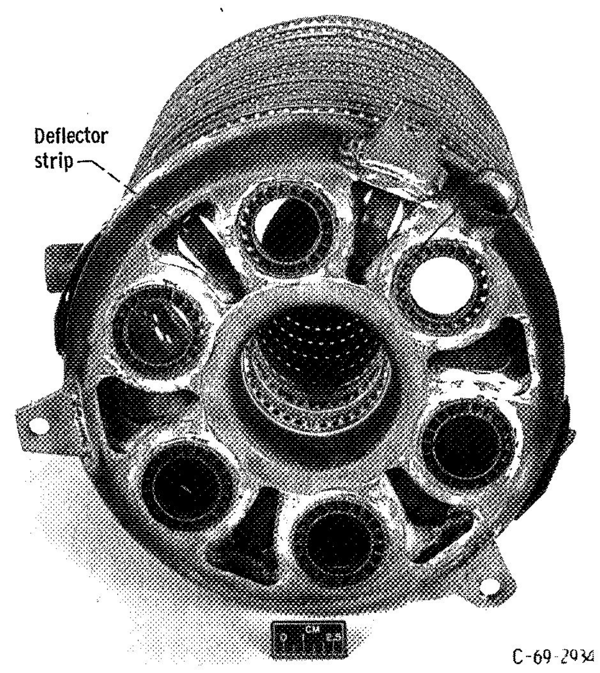


Figure 26. - Model 5-C; view of combustor dome (looking downstream).

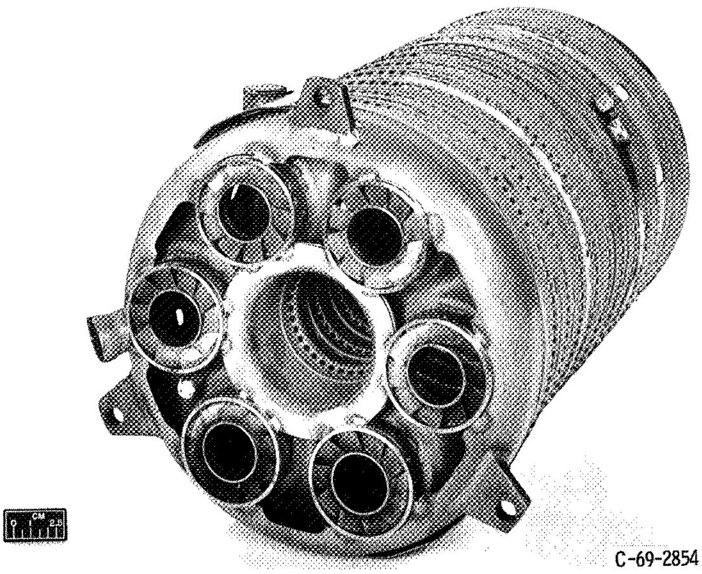


Figure 27. - Model 6-A; view of combustor dome (looking downstream).

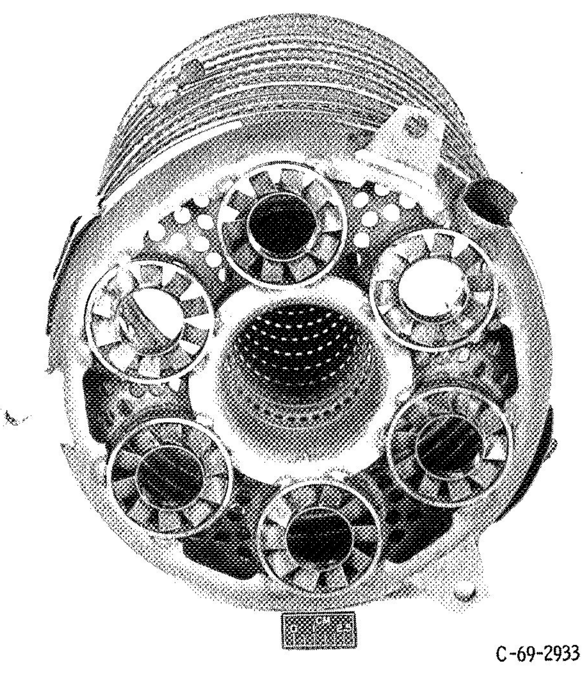


Figure 28. - Model 6-D; view of combustor dome (looking downstream).

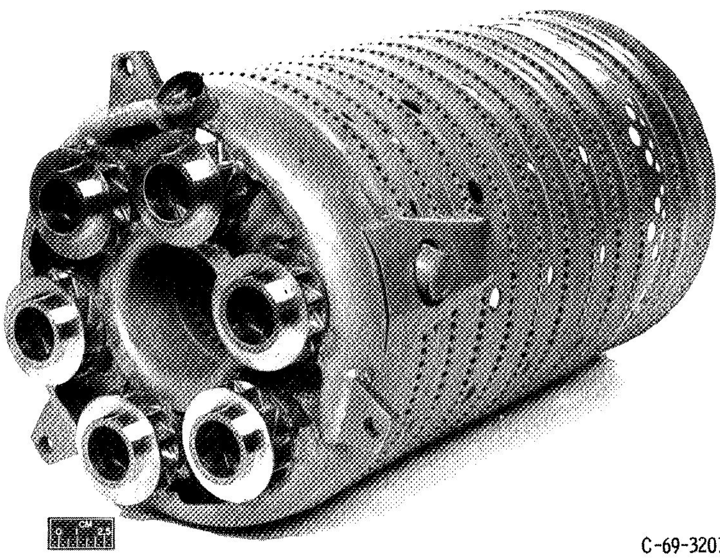


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Figure 29. - Model 6-E; view of combustor dome (looking downstream).

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